

# Forward Osmosis Brine Drying

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The Forward Osmosis Brine Drying (FOBD) system is based on a technique called forward osmosis (FO). FO is a membrane-based process where the osmotic potential between brine and a salt solution is equalized by the movement of water from the brine to the salt solution. The FOBD system is composed of two main elements, the FO bag and the salt regeneration system. This paper discusses the results of testing of the FO bag to determine the maximum water recovery ratio that can be attained using this technology.

Testing demonstrated that the FO bag is capable of achieving a maximum brine water recovery ratio of the brine of 95%. The equivalent system mass was calculated to be 95 kg for a feed similar to the concentrated brine generated on the International Space Station and 86 kg for an Exploration brine. The results have indicated that the FOBD can process all the brine for a one year mission for between 11% to 10% mass required to bring the water needed to make up for water lost in the brine if not recycled. The FOBD saves 685 kg and when treating the International Space Station brine and it saves 829 kg when treating the Exploration brine. It was also demonstrated that saturated salt solutions achieve a higher water recovery ratios than solids salts do and that lithium chloride achieved a higher water recovery ratio than sodium chloride.

## Nomenclature

<i>FOBD</i>	= Forward Osmosis Brine Drying
<i>FO</i>	= Forward Osmosis
<i>ESM</i>	= Equivalent System Mass
<i>Kg</i>	= Kilogram force
<i>KW</i>	= Kilowatt
<i>OA</i>	= Osmotic Agent
<i>DCMD</i>	= Direct Contact Membrane Distillation
<i>UPA</i>	= Urine Processing Assembly
<i>ISS</i>	= International Space Station
<i>ARFT</i>	= Advanced Recycle Filter Tank
<i>RR</i>	= Water Recovery Ratio
<i>DOC</i>	= Direct Osmotic Concentration
<i>NASA</i>	= National Aeronautics and Space Administration
<i>TOC</i>	= Total Organic Carbon
<i>WRR</i>	= Water Recovery Ratio

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## I. Introduction

This project evaluated the Forward Osmosis Brine Drying (FOBD) technology for the drying of spacecraft water recycling system brine byproducts. The FOBD system is composed of the FO bag and an OA regeneration system. The FO bag is a plastic bag, which is separated internally into two compartments by a membrane. This membrane allows water to pass from one side of the bag to the other but does not allow contaminants to pass through it. During the FO process, the water in the brine passes through the membrane and into the OA. This results in the brine becoming concentrated and the OA becoming diluted. The second element is the OA regeneration system, which removes the product water from the OA and re-concentrates the diluted OA. The FOBD can use either a direct contact membrane distillation system (DCMD), powered by a thermoelectric heat pump, or the Urine Processing Assembly (UPA) on the International Space Station (ISS) for regenerating the OA.

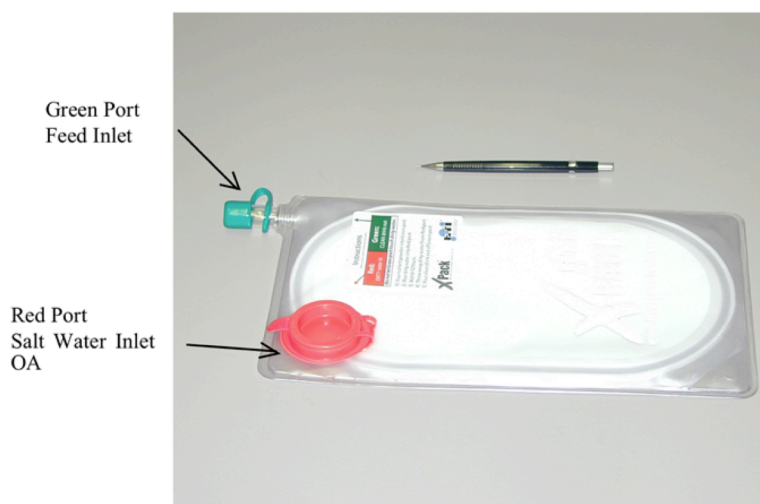
The purpose of this work is to evaluate the FO bag using feed streams composed of brines similar to those generated on board the International Space Station (ISS) and future exploration missions. This evaluation includes both analysis and experimental testing. The testing element includes operation of the FO bag with two brine formulations: ISS Alternate Pretreatment formula<sup>1</sup> and “Solution 2” which is an alternative pretreated exploration brine derived from the Distillation Down Select<sup>2</sup> (modified to use the ISS Alternate Pretreatment formula.<sup>3</sup>). The regeneration step was not evaluated experimentally but evaluated by analysis of previous testing conducted using an un-pretreated urine feed<sup>4</sup>.

## II. FOBD Equipment Description

The FOBD system is based on a technique called forward osmosis (FO). FO is a membrane-based process where the osmotic potential between two fluids of differing solute/solvent concentrations is equalized by the movement of solvent from the less concentrated solution to the more concentrated solution<sup>5,6,7,8</sup>. In FOBD, the urine brine is passed on one side of a membrane and a salt-water solution called the osmotic agent (OA) is passed on the other; the solvent is the water and the solutes are the urine solids in the brine.

The FOBD system is composed of two main elements: the FO bag and the OA regeneration system. The first element is the FO bag, which is separated into two compartments by a membrane that allows water to pass through. During FO, the water in the brine passes through a membrane and into the OA; this results in the brine becoming concentrated. The second element is the OA regeneration system, which removes the product water from the OA and re-concentrates the OA. For this study it is assumed that the FOBD uses a Direct Contact Membrane Distillation (DCMD) system powered by a thermoelectric heat pump for regenerating the osmotic agent.

The FOBD bag is based on the commercially available X-Pack™ (Figure 1), which is available through Hydration Technology Innovations in Albany, OR. The X-Pack has an inner membrane bladder sealed on two sides. Both sides of the bag have fluid connections so that it can be filled and emptied. The brine is placed on the inside of the membrane bladder (green inlet) and a concentrated solution (OA) is placed on the outside of the membrane bladder (red inlet).

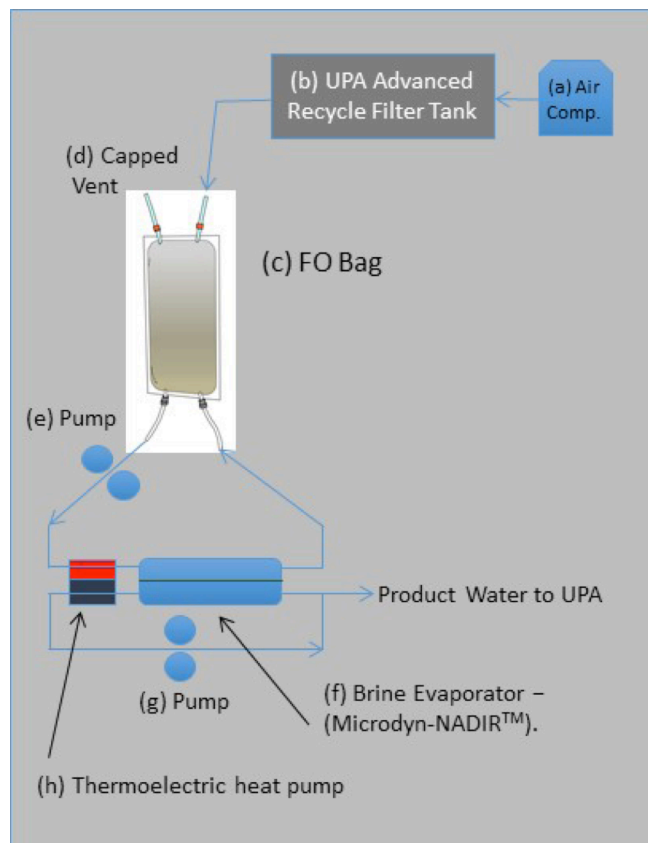


**Figure 1. Hydration Technologies X-Pack™ (FOBD).**

In the X-Pack the water that is removed from the brine dilutes the OA. This reduces the osmotic potential of the OA and the maximum water recovery ratio that can be achieved. If the OA is going to be reused it must be regenerated. In the FOBD, the OA is regenerated using a DCMD system. The DCMD process uses hydrophobic membrane and a heat pump to generate a temperature difference between the brine loop (the higher temperature side of the membrane) and the fresh water product receiving loop (the low temperature side). This temperature difference results in a vapor pressure differential across the membrane, which is the driving force for the water vapor flux through the pores of the membrane. The membrane used is composed of many uniform pores that are small enough that water forms a meniscus across them. This results in a liquid barrier across the pore of the membrane that will only allow water vapor to pass through.

Due to the fact that liquid is in direct contact with both sides of the hydrophobic membrane, this membrane evaporation is called Direct Contact Membrane Distillation. DCMD has been previously tested by NASA<sup>4</sup>. Testing of the DCMD is considered outside of the scope of this experimental work so the results of the earlier NASA testing are used for sizing and performance calculations in this study. Previous testing has shown that the DCMD is capable of achieving high water recovery ratios while rejecting urea, ammonia nitrogen, and rejecting some semi-volatile organics.

The configuration of the FOBD with the DCMD is shown in Figure 2. In this configuration, the urine brine is delivered to the FOBD in an ISS Advanced Recycle Filter Tank (ARFT) (b). The ARFT uses compressed air to discharge the contents of the tank (a). The urine brine is discharged into the FOBD FO bag (c). In the FO bag, water passes from the lower osmotic potential brine to the higher osmotic potential OA. The OA is then processed in the OA recovery system where the product water is recovered and the OA is reconstituted back to its original concentration. The OA recovery system is composed of a pump (e) that recirculates the OA through the FO bag (c) and a membrane evaporator (f). The membrane evaporator has the OA on one side and liquid product water on the other. The temperature of the OA and product are controlled by a thermoelectric heat pump (h) that recycles the latent heat of evaporation from the product back to the OA.



**Figure 2. FOBD integrated with DCMD to regenerate OA.**



**Figure 3. STS 135 FO bag test. Test validated filling and draining the FO bag in microgravity and completed initial evaluation of flux and ion rejection [5].**

The FO bag used in the FOBD concept is based on the flight version of the X-Pack, as shown in Figure 3. This bag was flown on the Space Shuttle mission STS 135 in 2011<sup>9</sup>, and is lighter than the XPack<sup>TM</sup>. Additionally, the bag has flight qualified quick-disconnects rather than the green and red ports of the XPack<sup>TM</sup>. Two versions of the flight bag were developed: the batch version, as shown in Figure 3; and a flow through system with two ports, which allows continuous flow through both sides of the bag, as shown in Figure 2 (c).

### 1. Alternative FOBD Configurations

Two additional integrated configurations for the FOBD have also been evaluated; these configurations are alternative methods to regenerate the OA. The first alternative configuration uses the ISS Urine Processing Assembly (UPA) to regenerate the OA. The second uses a solid OA followed by direct thermal regeneration of water vapor into the cabin environment. The first option is shown in Figure 4 and Figure 5. Figure 4 shows the FO bag in operation and Figure 5 shows the regeneration of the OA using the ISS UPA. This approach uses existing hardware on ISS to operate and regenerate the OA. The RFTA and a compressor are used to fill the FO bag and two Rodnik tanks are used to flow the OA through the bag, see Figure 4.

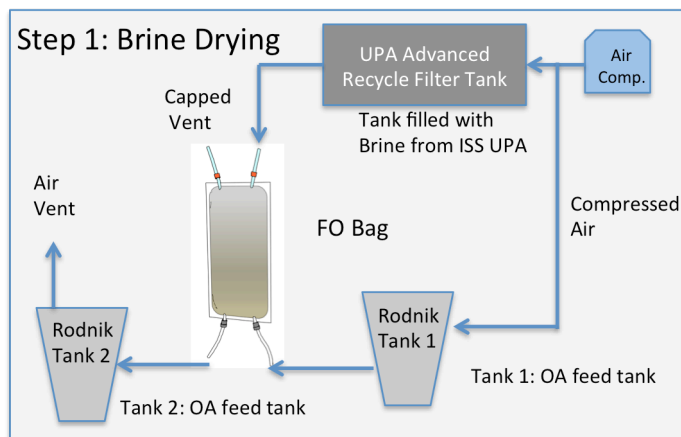
The OA in the Rodnik tanks are then regenerated by processing the OA through the ISS UPA, see Figure 5.

The second option is to use solid NaCl salt crystals as the OA. In this configuration, the outer plastic envelope of the FO bag is removed and the internal membranes are exposed directly to the rock salt. The OA salt is then regenerated by using direct heating and the evaporation of water to the spacecraft cabin, Figure 6.

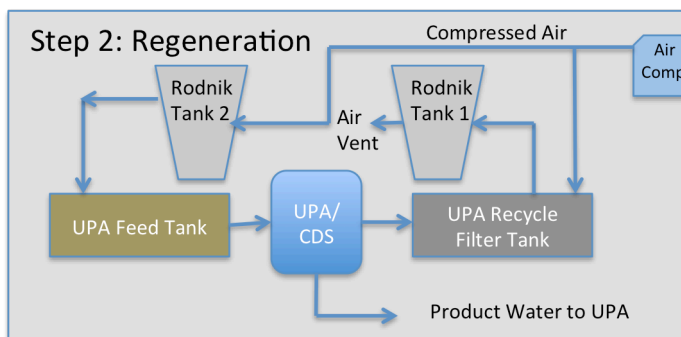
Testing of the rock salt option has shown that it reduces the maximum water recovery ratio that can be achieved; therefore, this method is not desirable. The use of the ISS UPA to regenerate the OA requires resolution of significant integration and approval issues that are outside of the scope of this study. As a result, the use of the DCMD evaporator, shown in Figure 2, is considered the baseline for testing in this study.

### III. Brine Generation

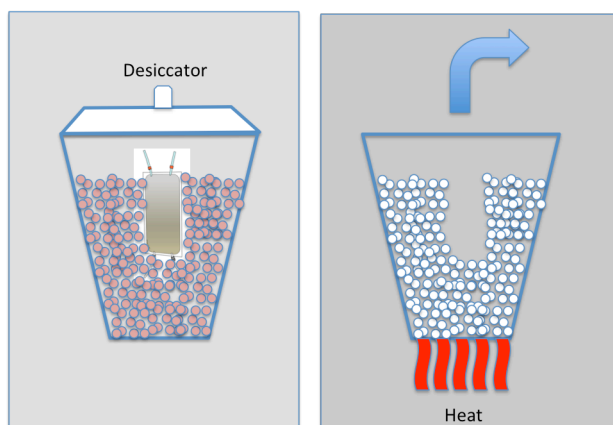
Brines were generated using the Wiped-film Rotating-disk (WFRD) evaporator. The WFRD a vapor compression distillation system that is used to simulate the function of the ISS Urine Processing Assembly (UPA). All tests were completed using urine collected from human donors that was then modified according to the



**Figure 4. Processing mode using Rodnik tanks as feed and waste containers for the OA.**



**Figure 5. Regeneration of waste OA in Rodnik tank using ISS UPA. Air Compressor, Rodnik tank, and Advanced Recycle Filter Tank exist on ISS.**



**Figure 6: Direct contact of FO membrane to solid OA followed by regeneration using heat and venting to cabin**

AES augmented urine procedure with a humidity condensate ersatz<sup>10</sup>. Hygiene water was generated from human subject shower water, hand wash, oral, and shaving water. Humidity condensate water was generated from a synthetic formula.

Urine was collected from male donors only. All donations were anonymous. The men's room collection device is composed of a double container and a funnel. During the collection period, the space between the two containers was filled with ice. Containers were placed in the restrooms at approximately 8 am and removed in the afternoon at approximately 5 pm. After the urine was collected pretreatment chemicals were added according to the brine formula required for testing. The urine was then refrigerated at  $4 \pm 2$  °C until use. Pretreated urine was stored for no longer than 2 weeks.

The WFRD was operated in a continuous mode where the flow rates of the feed, brine, and product were adjusted to values required for achieving the specified water recovery ratio (WRR). For the ISS Alternative Pretreat Formulation and the green treat formulation, the WFRD was operated at 85% WRR. For the Distillation Down Select Solution 2, the WFRD was operated at a 95% WRR.

#### **IV. Analytical Test Plan**

The FOBD feed (brine) and distillate was analyzed at NASA Ames laboratory for ionic composition (using ion liquid chromatography), TOC (using a non-purgable total organic carbon analyzer), density, and TDS. A Dionex ICS-1500 was used for cations and a Dionex DX-500 was used for anions. A Shimadzu TOC-V CSH combustion system was used for OA samples and a Shimadzu TOC-VWs/P was used for all other samples. The brine samples were sent to an outside laboratory to test for levels of Cr(VI) and Cr(III).

#### **V. FOBD Testing**

Testing of the FOBD was focused on determining the maximum WRR that can be achieved. This was because the FO process is limited in how high the RR can be by the osmotic potential of the OA. The tests conducted in this work evaluated three types of osmotic solvents, one using a saturated NaCl salt solution, one using solid granular NaCl salt, and one using a saturated lithium chloride solution. Tests were conducted for two types of brine feed. One was based on the ISS Alternative Pretreat (no hygiene water) urine and the other was an exploration formulation that included urine, hygiene water, and humidity condensate brine. The commercially available XPack<sup>TM</sup> was used for this testing.

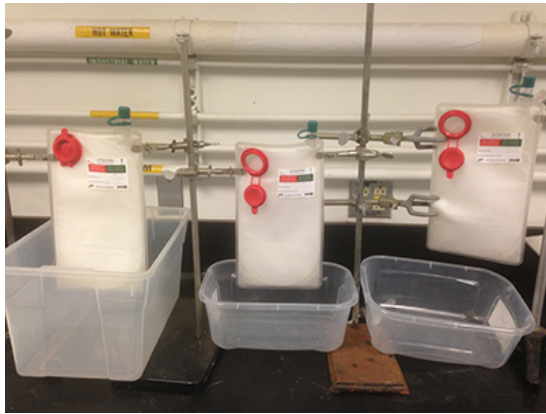
In addition to determining the WRR, this testing also provided mass, power, and volume data for the bag portion of the FOBD. Chemical analysis of the product was completed and limited analysis of the concentrated brine was completed. Testing of the systems to regenerate the OA was not covered in this work. Mass, power, and volume estimates for the OA regeneration system have been derived from earlier testing as part of the Direct Osmotic Concentration (DOC) project using similar DCMD system<sup>4</sup>.

##### **A. Saturated Salt OA Solution Test**

Three identical tests were run simultaneously for each brine. The brines used were the ISS Alternate Pretreatment brine and the Solution 2: Alt Pretreat brine. The bags were filled with brine and OA by placing them on ring stands vertically and pouring the brine and OA in through the bag ports, see Figure 7. The bags were then placed horizontally in a secondary container for the duration of the test, see Figure 8. The volume of the brine that was added to the FO bag of the FOBD (using the green inlet port) was 375 mL; the volume of the osmotic agent (using the red inlet port) was 1 L, see Figure 1. The concentration of the osmotic agent for sodium chloride was 350 g/L. The concentration of the osmotic agent for lithium chloride was 700 g/L. When filling the bag with the brine and OA, the FOBD was slightly squeezed with the cap open in order to remove air bubbles. This was done to maximize the surface area of the liquids against the membrane by insuring there was no air in the bag.

After running the tests for 24 hours, the volume of OA in each bag was measured to determine the water production rate across the membrane. To do this, the OA was drained from the bag by placing the FOBD upside down above a beaker and drained for 5 minutes. After collecting and measuring the volume of the OA, 1 L of the fresh OA (350 g of NaCl/L in deionized water) was poured into the same bag. Fresh OA was used to simulate regeneration of the OA. These steps were repeated every 24 hours until the water production rate leveled off.





**Figure 7. Three FOBDs ready for sample loading.**



**Figure 8. FOBDs are placed on their backs in a chemically resistant container during a run.**

### **B. Solid Salt OA Test**

Three identical tests were run simultaneously for each brine: ISS Alternate Pretreatment brine and Solution 2: Alt Pretreat brine. The volume of the brine added to the FOBD was 375 mL. The FOBD was modified so that the membrane bladder was fully exposed, as shown in Figure 9. Once the brine was added and air bubbles were eliminated. The bladder was then fully covered in a bucket of solid salt, see Figure 10. The solid salt acted as the OA. The initial mass of the salt was recorded to determine the change in the mass of the salt or the production rate. Additionally, the mass of the FOBD was recorded every 24 hours.

To determine the mass of the salt, the FOBD was removed from the salt. Since salt stuck to the membrane, see Figure 11, six Kimtech Delicate Task Wipers were used to gently wipe off each side of the bladder twice. The mass of the used wipes and the FOBD was then recorded. The salt and any unabsorbed solution was weighed and the mass was recorded. The salt was then replaced with fresh salt and the bags were placed back into the salt buckets and left to continue testing. At the conclusion of the test the FO bag bladders were removed and the amount of concentrated brine remaining in them was measured. Figure 12 shows the modified FO bags after being exposed to solid salts for 24 hours.



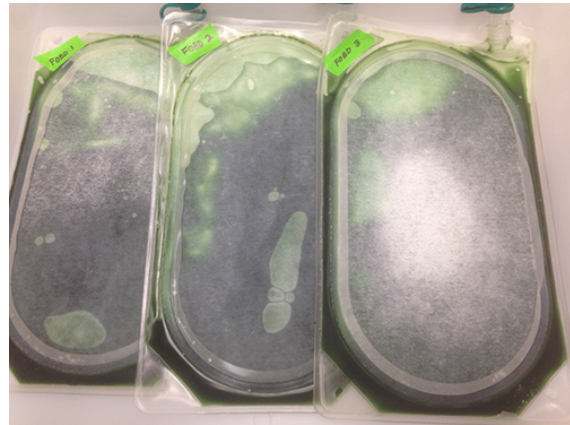
**Figure 9. An FOBD modified to have the membrane bladder fully exposed. The modification is the removal of the outer bag plastic walls to expose the inner FO membrane pouch.**



**Figure 10. The modified FO bag completely covered by salt for the Solid Salt OA Test.**



**Figure 11. Solid salt sticking to the FO bag.**

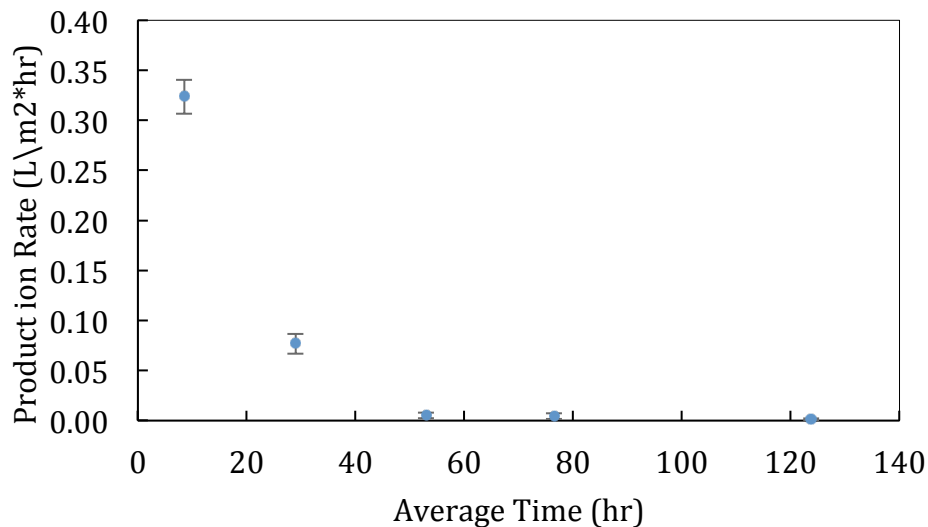


**Figure 12. Modified FO bags after being exposed to solid salts for 24 hours.**

## VI. Results

### A. Sodium Chloride Saturated Salt OA Results

Two saturated salt OA tests were conducted. The feed used for testing was Solution 2: Alt Pretreat brine and the ISS Alternative Pretreatment brine. In both cases the amount of product generated as a function of time was measured by recording the increase in volume of the OA. Figure 13 shows the production rate as a function of time. It shows the standardized production rate ( $L/m^2\text{-hr}$  or LMH) of the bag using saturated NaCl salt OA and the ISS Alternative Pretreat Brine. This data is generated by using the volume of water produced each day and dividing it by the 24 hours in a day and by the membrane area of the FO bag ( $0.035m^2$ ).

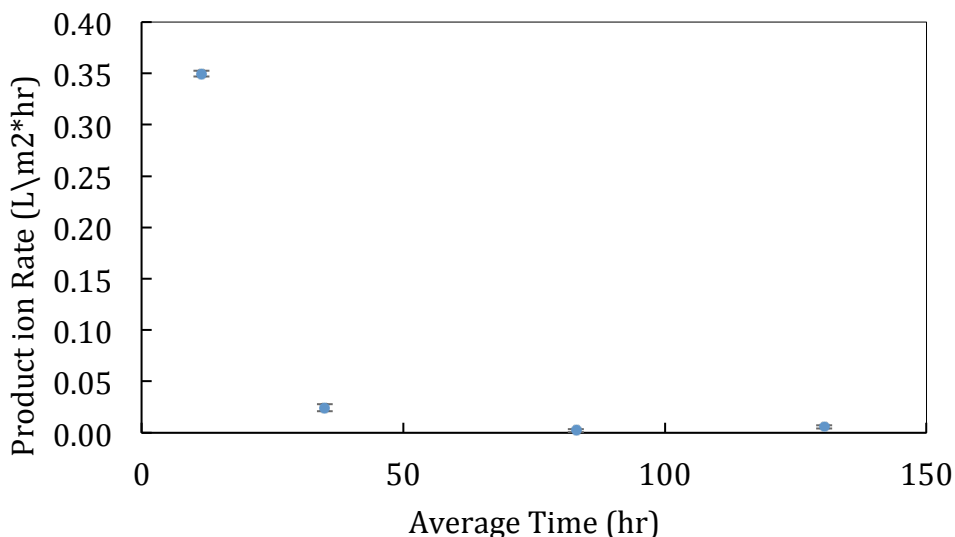


**Figure 13. Standardized production rate (LMH) of the product versus time with a saturated salt OA concentration of 350 g/mL and ISS Alternate Pretreatment brine.**

Figure 13 show that the production rate drops exponentially with time. As a result most of the water is recovered within the first 48 hrs. of the test. The By the third day, the amount of water removed from the brine is minimal. This exponential reduction in production is due to the increase in concentration of the feed that occurs as water is removed. As the concentration of salts in the feed and OA equalizes the process stalls.

Figure 14 shows the standardized production rate of the bag (LMH) using a saturated NaCl salt OA and Solution 2: Alt Pretreat brine as feed. This data is generated in the same was described earlier. The initial

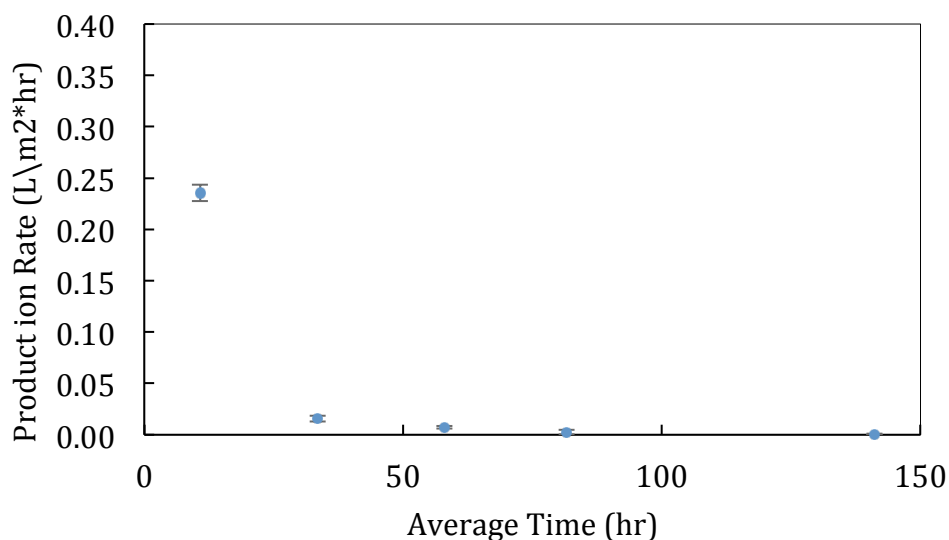
production rate was a bit higher and the rate falls off quicker than for the ISS Alternative Pretreat brine, shown in Figure 13. This is because the Solution 2: Alt Pretreat brine has a lower osmotic potential than the ISS Alternative Pretreat brine because it is diluted with hygiene water.



**Figure 14. Standardized production rate (LMH) versus time with a saturated salt OA and Solution 2: Alt Pretreat brine. Data represents the amount of water produced each day.**

#### B. Solid Salt OA Results

Figure 15 shows the standardized production rate (LMH) as a function of time for the solid salt solution OA tests using the ISS alternative pretreat brine. This plot was generated by removing the bag from the solid salt and measuring the increase in the weight of the solid salt once every day. The product rate drops exponentially with most of the water is recovered within 48 hr. of the start of the test. By the third day the amount of water removed is minimal. The production rate of the solid salt tests were lower than for the saturated salt solution. In addition, the total amount of water removed with the solid salt is lower than that removed with the saturated salt solution. The water recovery ratio achieved in these tests were also lower than the required value. The results of this test demonstrate that the saturated salt OA is better than the solid salt OA.



**Figure 17. Standardized production rate (LMH) versus time with a solid salt OA and ISS Alternate Pretreatment brine.**

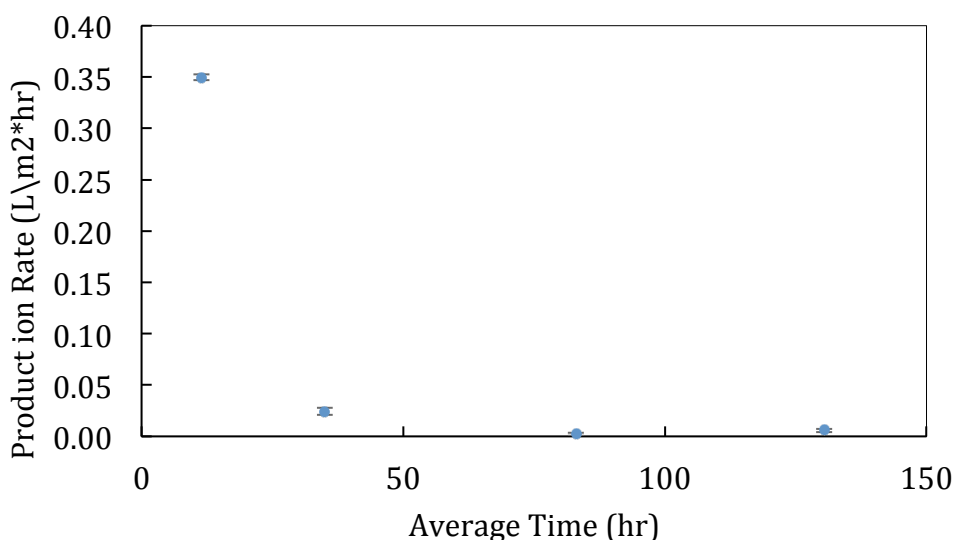


Testing of the solid salt with the Solution 2: Alt Pretreat bine was not completed because the results with the ISS alternative pretreat brine demonstrated that the solid salt OA was not capable of achieving a high enough water WRR to justify continuing testing.

### C. Lithium Chloride Saturated Salt OA Results

Lithium chloride was tested in order to evaluate the maximum WRR possible for the FOB. Lithium chloride has a higher solubility in water than NaCl. This gives it higher osmotic potential. Figure 18 shows the standardized production as a function of time for the lithium chloride saturated salt OA tests using the ISS alternative pretreat brine. This data was generated by draining the OA from the bag once every day and measuring the increase in volume of OA. After the OA was drained it was replaced with 1 L of a 700 g/L LiCl solution.

Figure 18 show that the water production rate decreases exponentially and most of the water is recovered within 48 h of the start of the test. By the third day, the amount of water removed from the brine was minimal. The rate of production is about the same as for the saturated NaCl solution, however, the LiCl OA achieved the highest WRR. The WRR of the saturated NaCl salt solution when treating the ISS Pretreat did not hit the WRR specification. Using LiCl increases the water recovery ratio to exceed the WRR specification. Therefor, the LiCl is the best OA to use for this application. It gets the highest WRR.



**Figure 18. Standardized production rate (LMH) of the product versus time with a saturated salt OA concentration of 350 g/mL and ISS Alternate Pretreatment brine.**

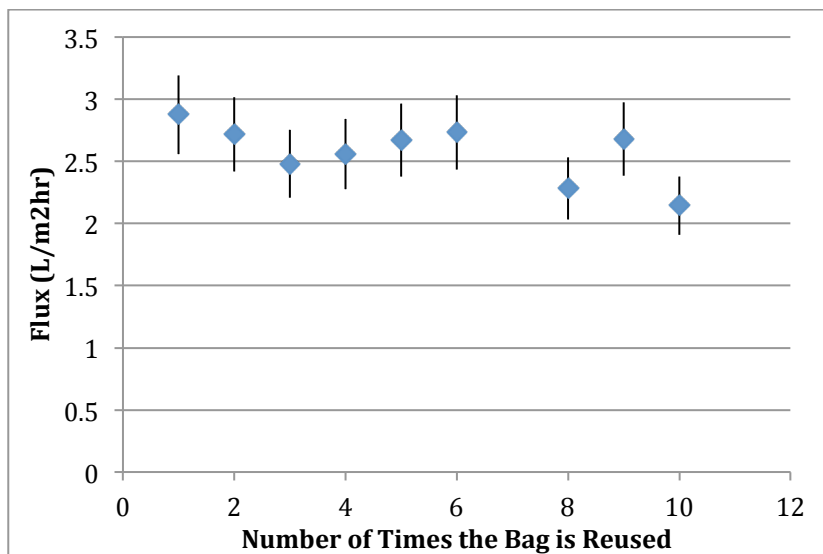
### D. Bag Reuse Testing

The bags were drained of concentrated brine by rolling them up to force the brine out. This was done to evaluate the ability to drain the concentrated brine and refill it with new brine. This approach would allow the bags to be used more than once. The brine was a viscous liquid at the required WRR. This process is shown in Figure 19. Testing has show that about 97.6% of the brine could be removed using this approach after the first reuse.

It is not known how many times the bags could be reused using the concentrated brine. However, earlier testing of the bags with un-pretreated urine has shown that the bag can be reused over 10 times with about a 25% reduction in flux<sup>11</sup>. These results are shown in Figure 20. All data points are averages of triplicate tests with the standard deviation of the three tests provided as error bars. For the entire data set the average is 2.6 L/m<sup>2</sup>hr, the standard deviation is 0.22, and the relative standards error is 8.5% indicating that reduction in production is a real effect. These tests achieved a 90% water recovery ratio with a urine feed and 35% NaCl in the OA. It is anticipated that with brine as the feed instead of urine, the life of the membrane will be reduced. This is due to the high solids content generated in the concentrated brine and its potential to foul the FO membrane. As a result, it is assumed that the performance will drop 50% after 10 reuses. This value will have to be validated in future experimental work.



**Figure 19. Microgravity brine discharge.**



**Figure 20. Reduction in flux as a function of the number of times a bag has been reused. This data is taken from earlier work with XPack technology [2]. It is based on concentrating urine to a brine.**

If we use a 50% linear reduction in production after 10 reuses, each bag will process 2.3 L/m<sup>2</sup>hr of brine. 2L of this will be product and 0.3 L concentrated brine. The brine can be reintroduced into an older expended FO bag where it can be stored during the mission.

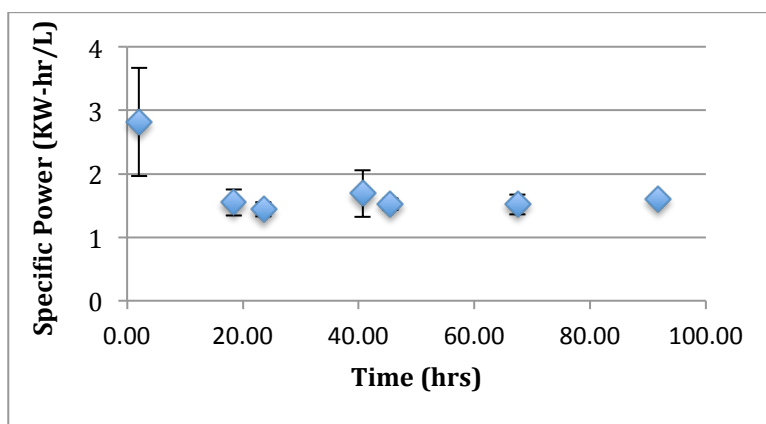
Table 1 provides basic data for all runs including the initial brine volume, brine density, volume and mass of product recovered, % volume reduction, and % water recovery ratio. The % mass water recovery ratio is corrected from volume measurements to mass values using the starting and ending density of the brine.

**Table 1. Percent mass and volume recoveries from FOBD testing.**

Test	Initial Brine Volume (mL)	Density of Brine (g/mL)	Volume Recovered (mL)	Mass Recovered (g)	% Volume Reduction	% Mass Water RR (m) product-brine	Target % Water RR (m)
NaCl Solution, ISS Alternative Pretreat Brine	375	1.14	268	NA	71	80+-3	86.7
NaCl Solution, Solution 2: Alt Pretreat Brine	375	1.2	311	NA	83	89+-3	84.4
NaCl Solid Salt ISS Alternative Pretreat Brine	375	1.2	NA	199	NA	74+-6	86.7
LiCl Solution, ISS Alternative Pretreat Brine	375	1.15	267	NA	71	87+-7	86.7

#### E. Power Data Analysis

The FO bags tested do not consume any power; however, the regeneration of the OA does. Regeneration of the osmotic agent using a direct contact membrane distiller (DCMD) will consume power. Data for the power consumption of the DCMD was developed previously by our laboratory as part of the Direct Osmotic Concentration (DOC) technology development project in 2004<sup>4</sup>. Figure 21 shows the results of three tests of the DCMD with un-pretreated urine as the feed. The maximum WRR achieved was 90%. Although testing with the actual brine will be required prior to completing any final FOBD design, the DCMD data provides a rough order of magnitude of power consumption to support calculation of ESM values for the FOBD.

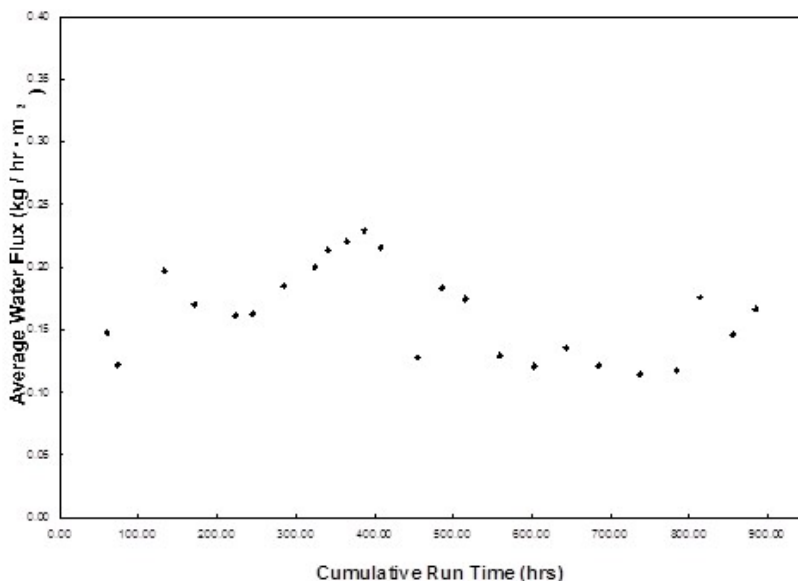


**Figure 21. The graph of specific power [kWh/L-product] for run 2, 3, and 4. The average power for these three runs is 1.7 kWh/L and the maximum is 3.7 KWh/L at the start.**

For the ESM calculations the Cascade Distillation thermoelectric heat pump was used as the example system<sup>12</sup>. This system was sized linearly to fit this application based on mass and volume. The power consumption was fitted to the 1.7KWh/L value determined in DCMD testing. This is because the thermoelectric heat pump testing

did not account for the real world heat losses in the DCMD system. The 1.7 kWh/L value is based on integrated testing.

Figure 22 shows the normalized production rate (flux) for the DCMD tests. This figure presents the information required to size the OA regeneration membrane evaporator. The average flux rate of 0.14 kg/m<sup>2</sup>hr is used for ESM calculations.



**Figure 22. DCMD normalized flux rate. Data is a compilation of three sequential runs. Average is 0.14 kg/m<sup>2</sup>hr. Water RR for all three runs was 90%.**

## F. Analytical Results

Samples of the OA were tested for Ions, non-purgable total organic carbon (TOC), chromium, and total dissolved solids (TDS) for saturated salt urine and hygiene runs. This testing was conducted to evaluate if the OA could be further treated in a dedicated OA regeneration system such as the DCMD or the ISS UPA. Table 12 provides the results of this analysis. The analysis was only performed on the saturated NaCl salt tests. The table shows that the only ions in the OA are Na<sup>+</sup> (average 99,663 mg/l) and Cl<sup>-</sup> (average 201,815 mg/l). This is expected because these ions are the osmotic agent. Chromium levels were low with an average of less than 1 mg/l. Hexavalent chromium was found in the feed but not in the OA. TOC levels are relatively high and averaged 2845 mg/l. The total solids of the end point brine was high, 737 mg/l. In general the results indicate that chemical composition of the OA is appropriate for post treatment in a urine treatment system such as the ISS Urine Processing Assembly (UPA) or the DCMD.

**Table 12. Ions, TOC, chromium, and TDS for saturated salt urine and hygiene runs.**

Sample I.D.	Na	NH4	K	Mg	Ca	Cl	NO2	Br	NO3	PO4	SO4	Cr	TOC	TDS
<b>Urine feed data - All values in mg/L</b>														
Urine, Bag1-1	98922	ldl	ldl	ldl	ldl	202253	ldl	ldl	ldl	ldl	ldl	0.11	10260	nt
Urine, Bag2-1	85684	ldl	ldl	ldl	ldl	168467	ldl	ldl	ldl	ldl	ldl	0.25	7315	nt
Urine, Bag3-1	84107	ldl	ldl	ldl	ldl	175295	ldl	ldl	ldl	ldl	ldl	0.29	6571	nt
Urine, Bag1-2	99545	ldl	ldl	ldl	ldl	214238	ldl	ldl	ldl	ldl	ldl	ldl	4362	nt
Urine, Bag2-2	99427	ldl	ldl	ldl	ldl	201222	ldl	ldl	ldl	ldl	ldl	0.06	4498	nt
Urine, Bag3-2	104755	ldl	ldl	ldl	ldl	207760	ldl	ldl	ldl	ldl	ldl	0.82	4388	nt
Urine, Bag1-3	100485	ldl	ldl	ldl	ldl	204702	ldl	ldl	ldl	ldl	ldl	nt	3133	nt
Urine, Bag2-3	106620	ldl	ldl	ldl	ldl	214698	ldl	ldl	ldl	ldl	ldl	nt	2926	nt
Urine, Bag3-3	101812	ldl	ldl	ldl	ldl	207429	ldl	ldl	ldl	ldl	ldl	nt	2634	nt
Urine, Bag1-4	97111	ldl	ldl	ldl	ldl	203385	ldl	ldl	ldl	ldl	ldl	nt	1322	nt
Urine, Bag2-4	107776	ldl	ldl	ldl	ldl	205653	ldl	ldl	ldl	ldl	ldl	nt	1274	nt
Urine, Bag3-4	101936	ldl	ldl	ldl	ldl	204782	ldl	ldl	ldl	ldl	ldl	nt	1620	nt
Urine, Bag1-5	99631	ldl	ldl	ldl	ldl	203829	ldl	ldl	ldl	ldl	ldl	0.55	2085	664
Urine, Bag2-5	99049	ldl	ldl	ldl	ldl	204522	ldl	ldl	ldl	ldl	ldl	0.72	1932	706
Urine, Bag3-5	102557	ldl	ldl	ldl	ldl	211593	ldl	ldl	ldl	ldl	ldl	1.00	2378	726
<b>Hygiene feed - All values in mg/L</b>														
Hygiene, Bag1-1	75367	ldl	ldl	ldl	ldl	148653	ldl	ldl	ldl	ldl	ldl	0.26	6633	nt
Hygiene, Bag2-1	72040	ldl	ldl	ldl	ldl	145041	ldl	ldl	ldl	ldl	ldl	0.33	6865	nt
Hygiene, Bag3-1	72823	ldl	ldl	ldl	ldl	149354	ldl	ldl	ldl	ldl	ldl	0.31	7394	nt
Hygiene, Bag1-2	100337	ldl	ldl	ldl	ldl	208766	ldl	ldl	ldl	ldl	ldl	0.07	1765	nt
Hygiene, Bag2-2	97086	ldl	ldl	ldl	ldl	200696	ldl	ldl	ldl	ldl	ldl	0.11	2458	nt
Hygiene, Bag3-2	97427	ldl	ldl	ldl	ldl	230759	ldl	ldl	ldl	ldl	ldl	0.12	2075	nt
Hygiene, Bag1-3	100933	ldl	ldl	ldl	ldl	214817	ldl	ldl	ldl	ldl	ldl	nt	1765	nt
Hygiene, Bag2-3	100234	ldl	ldl	ldl	ldl	212213	ldl	ldl	ldl	ldl	ldl	nt	1958	nt
Hygiene, Bag3-3	97470	ldl	ldl	ldl	ldl	208403	ldl	ldl	ldl	ldl	ldl	nt	1753	nt
Hygiene, Bag1-4	103773	ldl	ldl	ldl	ldl	221766	ldl	ldl	ldl	ldl	ldl	nt	517	nt
Hygiene, Bag2-4	98290	ldl	ldl	ldl	ldl	210680	ldl	ldl	ldl	ldl	ldl	nt	511	nt
Hygiene, Bag3-4	98580	ldl	ldl	ldl	ldl	210126	ldl	ldl	ldl	ldl	ldl	nt	489	nt
Hygiene, Bag1-5	97117	ldl	ldl	ldl	ldl	208967	ldl	ldl	ldl	ldl	ldl	nt	446	nt
Hygiene, Bag2-5	102318	ldl	ldl	ldl	ldl	222188	ldl	ldl	ldl	ldl	ldl	nt	522	nt
Hygiene, Bag3-5	96214	ldl	ldl	ldl	ldl	209769	ldl	ldl	ldl	ldl	ldl	nt	639	nt
Hygiene, Bag1-6	96463	ldl	ldl	ldl	ldl	208737	ldl	ldl	ldl	ldl	ldl	2.60	478	854
Hygiene, Bag2-6	95733	ldl	ldl	ldl	ldl	207148	ldl	ldl	ldl	ldl	ldl	3.30	557	742
Hygiene, Bag3-6	98539	ldl	ldl	ldl	ldl	211994	ldl	ldl	ldl	ldl	ldl	5.00	369	757

ldl = lower detection limit, typically 0.5 ppm

nt = not tested

## VII. Resupply/Consumables

The primary resupply requirement is the FO bags. These bags have a limited life due to fouling of the FO membranes by solids that precipitate out of solution from the brine as it is concentrated. The commercial XPack bag weighs on average 134.2 g. The fight version tested on STS 135 weighed 81g and advanced development estimates



have been published as low as 50 g<sup>13</sup>. Figure 23 shows the side-by-side comparison of the commercially available XPack and a custom bag weighing 50g. For calculating ESM values, the flight tested 81 g STS 135 bag shown in Figure 2 will be used for all calculations.



**Figure 5. Side by side comparison of XPack bag weighing 134 g and an advanced development FO bag weighing 50 g.**

The other resupply will be salt. The FO membrane loses on average 0.2g of salt per L of product. For a transit mission of ½ year duration this equates to 78 grams for the Solution 2: Alt Pretreat brine and 93 grams for the ISS Alternative brine. Equivalent System Mass Calculations

ESM values are determined using data from the 2008 Baseline Values and Assumptions Document (BVAD) for a 360-day Mars transit mission<sup>14</sup>. Two cases are examined, one that uses the ISS Alternate Pretreatment brine/feed with the LiCl OA and one that uses the Solution 2: Alt Pretreat brine feed with the NaCl OA. Although testing focused only on bag performance, a complete system that includes OA regeneration was examined for the calculation of ESM values. All components used in the OA regeneration were based on commercial off the shelf components except for the FO bag, which was based on the NASA flight article tested on STS 135 and the thermoelectric heat pump which is based on a NASA system<sup>13</sup>. Table 2 provides a list of the mass, power, and volume for all components of a complete FOBD system. Bag usage was estimated by assuming that the XPack format was maintained and replacement bags provided as needed. This is a significant simplification as a larger FO bag that is better suited for automated filling and draining is warranted for the final design.

**Table 2. Mass, power, and volume for FOBD system.**

Component	Qt	Mass (Kg)	Power (KW)	Volume (m <sup>3</sup> )
X-Pack- Flight Version	1	0.081	0	0.004
Evaporator	1	2.0	0	0.0015
Pump	2	0.91	0.02	0.0015
Thermoelectric Heat Pump	1	4.5	0.133	0.0028
Plumbing	Na	1.00	0	0.01

FOBD specific assumptions used to calculate the ESM are:

- Bags can be reused 10 times with a linear decrease in flux of 50% over the 10 reuses, see
- Figure.
- Solution 2: Alt Pretreat feed is 2.14kg of brine per day
- ISS alternative feed is 2.56 kg of brine per day
- Although the final design of the bag has not been completed the 2.14 L or 2.56 L / 2.3 L ratio is used to determine how many bags will need to be resupplied for a give mission. This represents a conservative upper bounds on bag replacement.
- Energy consumption is based on the average value determined during DCMD testing, see
- Figure .
- Crew time estimates have not be provided pending better definition of what a flight system would look like.

The calculated ESM are:

ESM for Solution 2: Alt Pretreat mission feed is 86 Kg.

ESM for the ISS pretreat is 95 kg.

For a 360-day long Mars transit mission, 770 kg of Solution 2: Alt Pretreat brine and 921kg of ISS Alternative Pretreated brine would be produced if no brine drying technology was used. The water in this brine would have to be resupplied. Using the FOBDSaves about 89% to 90% of this water. The breakeven point for the Solution 2: Alt Pretreat mission feed is about 44 days and for the ISS Alternative feed is about 37 days.

## **VIII. Conclusions**

The FOBDS system was able to treat both the Solution 2: Alt Pretreat brine and the ISS Alternative Pretreat brine. It was able to achieve the targeted 84.4 % WRR for the Solution 2: Alt Pretreat brine using NaCl as an OA and the targeted 86.7% WRR for the ISS Alternative Pretreat brine using LiCl as an OA. It was not able to achieve the targeted 86.7% WRR for the ISS Alternative Pretreat using the NaCl OA. ESM calculations based on integration with the DCMD technology for OA regeneration resulted in 86 kg for the Solution 2: Alt Pretreat brine and 95 kg for the ISS Alternative Pretreat brine (using LiCl OA). This difference is due primarily to the difference in the starting salinity of the brines and the resulting brine volume produced in the primary urine processors (WFRD).

Upon completion of the three tests, we found that the saturated NaCl salt solution as an OA achieved a higher water RR rate than the solid NaCl salt, 76% versus 69%. As a result it has been determined that the liquid OA works better than the solid OA even though the solid OA has a much higher osmotic potential.

The bag format is not well suited to the development of an automated system. Although it has been tested in microgravity it may not be the ideal flight format. Modifications may be required to achieve the ultimate performance out of this technology. For example, making it larger and developing automated filling and draining approaches will reduce crew time requirements. To do this will require long duration testing to verify membrane life when treating concentrated brines.

The FOBDS also has a very low ESM and can process all the brine for a year long mission for between 11% to 10% mass required to bring the water needed to make up for water lost in the brine if not recycled. In other words, when used to treat the Solution 2: Alt Pretreat brine the FOBDSaves 685 kg and the ISS Alternative Pretreat brine saves 829 kg.

The function of the FO bag has been verified in flight. This testing verified that the FO process works in microgravity and the bag can be filled and product removed from it. It also showed contaminate rejection is unchanged from that on the ground but that there is a reduction in flux across the membrane in microgravity. This was a qualitative test and more flight testing needs to be done to quantify this reduction and develop mitigation approaches. This microgravity induced reduction in flux could be a significant issue for a final design.

The FO bag provides two levels of containment. The first is the outer envelope of the bag, which is made of plastic that is resistant to degradation. The second is the internal FO membrane pouch that contains the brine. Due to the high osmotic potential of the brine, once the brine is concentrated no water can pass through the membrane, as shown in Figure 12.

The FOB system does not produce any vapor that is discharged to the cabin. This mitigates odor and safety concerns associated with direct vent to the cabin. This also facilitates integration of the system with the ISS because product water can be directly reintroduced into the feed of the UPA as a liquid, which is essentially where it came from. Venting to the cabin opens up a number of issues associated with human health and safety and odor issues as well as compatibility issues with the condensing heat exchanger and WPA.

The FOB can be used as a stand alone brine dryer, when integrated with the DCMD, or as an integrated system designed to work with the ISS UPA for OA regeneration. The ESM calculations used in this analysis are derived from its use as a stand alone system using the DCMD.

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